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Distribution of niobium during chlorine processing of various titanium-containing feedstocks

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Abstract. This article presents the results of a study on the distribution of niobium during the chlorination processing of various titanium-containing feedstocks, including titanium slag from JSC «UK TMP», titanium slag from the Norwegian company TiZir Titanium & Iron AS, and their mixtures in different ratios. The titanium slag samples were ground and treated by chlorination using concentrated gaseous chlorine in a molten salt medium composed of alkali metal chlorides ($MgCl_2$, KCl, NaCl), with finely crushed anthracite as a carbon-based reducing agent. The process was conducted at temperatures from 700 to 820°C. The study focused on the distribution behavior of vanadium and niobium during the chlorination of blended titanium slags in proportions of 60/40, 50/50, and 30/70 (UK TMP/TiZir), as well as in 100% UK TMP slag. The results indicate that most of the niobium accumulates in the dump slag of the titanium chlorinator and in the slurry of the irrigated scrubber. It was also found that an increase in the initial niobium content in the feed leads to its higher concentrations in the sublimate of the dust chamber, in the melt of the salt bath dust-settling chamber, and in the scrubber slurry, while its share in the dump slag decreases.

Keywords: *titanium slag, vanadium, niobium, distribution, titanium, dump slag, chloride sublimates, chlorination, slag processing, niobium recovery.*

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1. Introduction

Improving the comprehensiveness of raw material processing and increasing the recovery of valuable accompanying elements is one of the primary objectives in modern extractive metallurgy. This is particularly relevant for complex feedstocks that contain multiple strategic or rare elements, whose inefficient recovery can lead to significant economic and environmental losses. Among such materials, titanium-containing feedstocks – such as ilmenite concentrate and titanium slag are known to contain a range of valuable metals, including rare and dispersed elements such as vanadium, niobium, tantalum, scandium, and zirconium [1, 2]. However, only vanadium and scandium currently have established industrial-scale recovery processes in the titanium production chain, while other critical elements are typically lost in waste streams [3].

Niobium (Nb), a strategic refractory metal with an average crustal abundance of 2×10^{-3} wt.% [4], plays a vital role in a wide array of high-technology applications. These include the manufacture of advanced structural materials, catalysts, superconducting systems, and electronics. Its main commercially exploited minerals are pyrochlore and columbite-tantalite, although it is also present in smaller quantities in perovskite, loparite, and ilmenorutile [5]. In many titanium ores, particularly ilmenite, niobium occurs in isomorphous substitutional positions, replacing titanium or iron due to its similar ionic radius and valence states. This complicates selective extraction during both reductive smelting and chlorination processing stages.

As shown in Figure 1, the global production of primary niobium feedstocks (mostly pyrochlore concentrates from Brazil and Canada) has increased steadily between 2001 and 2014, reflecting growing demand for niobium-containing materials in structural alloys and high-performance steels. Secondary sources of niobium, such as tin slag and tantalum-bearing minerals, contribute only marginally to the overall global supply (Figure 2). This supply imbalance highlights the importance of developing technologies for niobium recovery from alternative and non-traditional sources, including titanium-bearing slags.

One of the unique geochemical properties of niobium is its pronounced affinity to titanium and iron, which leads to the formation of a range of complex oxide and oxide-fluoride phases during natural and industrial processes. This includes the development of solid solutions such as $FeNb_2O_6$ and $CaNb_2O_6$, as well as the stabilization of niobium within perovskite- and rutile-type crystal structures [6]. As a result, niobium is commonly encountered as a trace element in a variety of titanium ores, which are often processed without consideration for its recovery. This represents both a missed economic opportunity and a challenge for resource sustainability.

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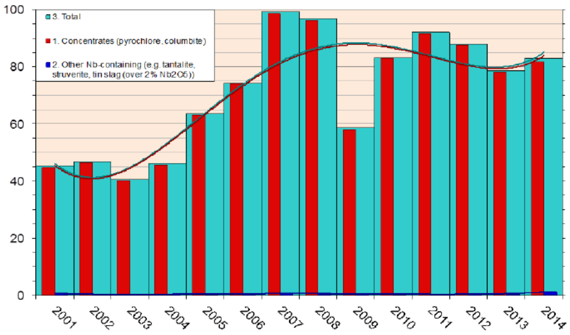

Figure 1. Production of primary niobium raw materials in 2001-2014

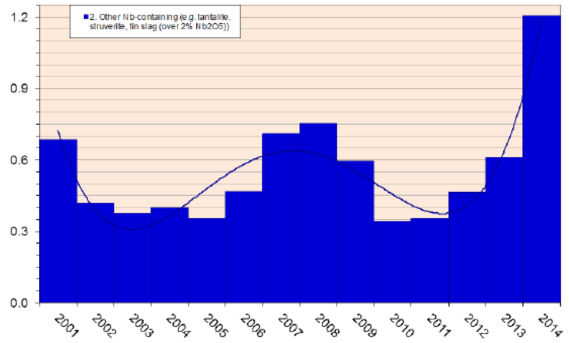

Figure 2. Production of secondary niobium raw materials in 2001-2014

Technologically, niobium is indispensable. It is widely used in the production of high-strength low-alloy (HSLA) steels, superconducting magnets (NbTi, Nb_3Sn), nuclear reactor components, aerospace alloys, electronics, and medical devices. As illustrated in Figure 3, approximately 87% of the global niobium consumption is in the form of steel-grade ferroniobium, which is added to microalloyed steels used in pipelines, automotive structures, and civil engineering. These steels typically contain ~0.05 wt.% Nb in HSLA grades and 0.04-0.08 wt.% in stainless steels. The remaining 13% of niobium is used in high-purity applications, including vacuum-grade alloys, chemicals (such as catalysts), and pure metal products [7].

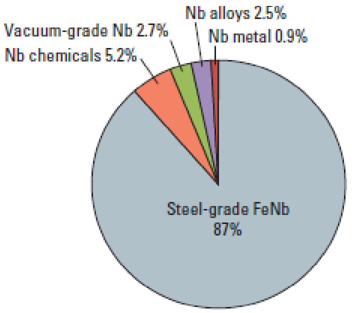

Figure 3. Niobium consumption by end-use sectors

The global niobium market is highly concentrated. Brazil accounts for approximately 90% of the total production, followed by Canada (~8%) (Figure 4). The world's leading producers CBMM (Companhia Brasileira de Metalurgia e Mineração), Mineração Catalão de Goias (both in Brazil), and IAMGOLD Corporation (Canada) dominate the supply chain and export primarily ferroniobium and niobium oxide products [8].

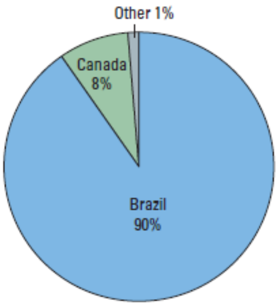

Figure 4. Niobium-producing countries

In 2012, the global output reached 53.5 thousand tonnes (Nb content), up from 52.2 thousand tonnes in 2011, reflecting a steady increase in demand from the steel and aerospace sectors [9].

Despite its strategic and economic importance, the industrial extraction of niobium from complex oxide matrices such as titanium slag remains challenging. Traditional pyrometallurgical or hydrometallurgical routes are not always viable, especially given niobium's high thermodynamic stability in refractory phases such as Nb_2O_5 and its low reactivity under standard chlorination conditions. In the presence of titanium oxides, niobium tends to be retained within solid solutions or form refractory compounds that resist volatilization or selective leaching. This makes it difficult to co-recover niobium during typical processing of titanium ores or slags.

The issue is particularly pronounced during the chlorination of titanium slag, a material produced from the reductive smelting of ilmenite concentrate. Depending on the origin and processing route, titanium slag may contain up to 0.12 wt.% Nb_2O_5, which corresponds to approximately 0.08 wt.% metallic niobium. While this may appear minor, in large-scale operations (20 thousand tonnes per year), this translates to potential niobium losses of 16 tonnes annually. Without targeted recovery, this valuable metal is lost with waste streams such as chlorinator dump slag, sublimates from the dust chambers, salt bath residues, and wet scrubber slurry.

Recent studies suggest that the behavior of niobium during slag chlorination is influenced by multiple factors, including temperature, partial pressure of chlorine, presence of reducing agents like carbon, slag composition, and the configuration of the chlorination system. In optimized systems that use molten salt media ($NaCl – KCl – MgCl_2$) and fine anthracite, partial conversion of niobium into volatile chlorides (NbC_5) and oxychlorides ($NbOCl_3$) becomes feasible. However, due to the relatively high Gibbs free energies of the required reactions, volatilization yields remain modest, and significant fractions of niobium persist in condensed phases.

Thus, to enable the recovery of niobium as a co-product during titanium tetrachloride ($TiCl_4$) production, it is essential to study its phase transformations and distribution across process streams in real industrial environments. Most prior research has focused on ilmenite concentrates and laboratory-scale experiments. There is a lack of data on industrial chlorination of titanium slag, especially from different geological and technological origins, and on the impact of feed blending on niobium recovery potential.

This study seeks to fill this knowledge gap by performing a comparative analysis of niobium distribution during the industrial chlorination of titanium slags from two different producers: JSC «UK TMP» (Kazakhstan) and TiZir Titanium & Iron AS (Norway). The research evaluates pure and blended feeds (100/0, 60/40, 50/50, and 30/70 ratios) under standardized chlorination conditions. The results provide a basis for understanding how feedstock composition, thermodynamic environment, and operational parameters influence niobium recovery.

The novelty of this research lies in the integration of industrial-scale experimental data with thermodynamic modeling to characterize niobium's phase behavior, chlorination kinetics, and final distribution. The insights gained can guide the development of selective co-recovery technologies for niobium and support more sustainable utilization of titanium-bearing feedstocks.

2. Materials and methods

The research utilized a variety of titanium-bearing raw materials and chlorination reagents. The primary materials were titanium slags obtained from two major industrial sources: JSC «UK TMP» (Kazakhstan) and TiZir Titanium & Iron AS (Norway). These slags were selected due to their distinct genesis and chemical composition, offering a representative spectrum for analyzing niobium distribution. The slags are formed via high temperature carbothermic reduction of ilmenite concentrates using anthracite as a carbonaceous reducing agent. Their physicochemical characteristics significantly influence the behavior of niobium and associated elements during chlorination [10-15].

The average chemical composition of the titanium slags is presented in Table 1. The Kazakh slag is notably rich in TiO_2 (85.12 wt.%) and contains elevated amounts of vanadium pentoxide (7.67 wt.%) and iron oxide (7.08 wt.%), while the Norwegian slag features a slightly lower TiO_2 content (84.79 wt.%) and significantly reduced vanadium (0.486 wt.%), making it suitable for comparative evaluation. Minor impurities such as Al_2O_3, CaO, MgO, Nb_2O_5, and trace quantities of rare-earth oxides (Sc_2O_3, Ta_2O_5, ZrO_2) were also recorded, reflecting the natural variability in ilmenite deposits.

Table 1. Average chemical composition of titanium slags (wt.%)

Type of slag	Average content, %													
	TiO_2	FeO	SiO_2	V_2O_5	Al_2O_3	CaO	MgO	Cr_2O_3	Sc_2O_3	Ta_2O_5	Nb_2O_5	MnO	S	ZrO_2
UK TMP	85.12	7.08	3.59	7.67	2.19	0.26	1.23	0.51	0.00	0.00	0.04	1.97	0.12	0.22
TiZir	84.786	7.854	2.292	0.486	2.006	0.125	1.3204	0.274	0.002	0.002	0.0602	1.666	0.0386	0.212

The chlorination reagents comprised AM-grade powdered anthracite and industrial-grade chlorine gas (minimum 90% vol. purity). These were selected based on compatibility with standard chlorinator systems used at titanium production facilities.

The experimental procedure consisted of a dual approach:

– thermodynamic modeling using HSC Chemistry 6.0 to simulate relevant chlorination reactions;

– validation through industrial-scale chlorination trials over the temperature range of 700-820°C.

Gibbs free energy (ΔG) values were calculated to assess the spontaneity and feasibility of reactions involving niobium- and titanium-containing phases, including the formation of volatile chlorides and intermediate oxychlorides.

The physical chlorination experiments were carried out using molten-salt chlorinators designed to simulate real production conditions. The chlorinator (Figure 5) was a cylindrical, steel-shelled, refractory-lined unit equipped with tuyeres for chlorine gas injection, upper and lower slag tapping ports, and a loading system for solid feedstock and reducing agent. The interior contained a melt of alkali metal chlorides (KCl, NaCl, $MgCl_2$) that served as both reaction medium and heat transfer agent. Slag samples were first crushed, milled to a particle size ≤0.16 mm, and dried before being introduced into the chlorinator alongside anthracite.

During operation, the chlorine gas was introduced through a tuyere system at the lower zone of the reactor, promoting chlorination within the molten salt bath. The process generated a vapor-gas mixture enriched in titanium tetrachloride ($TiCl_4$), volatile vanadium and niobium chlorides, and gaseous by-products. The gas phase was routed through a multistage condensation system consisting of a dust chamber, salt bath condenser, scrubber, and cryogenic condenser to selectively recover components based on their boiling points.

Uncondensed tail gases (CO, CO_2, Cl_2, O_2, N_2, HCl) were evacuated via exhaust fans and routed to a gas purification unit.

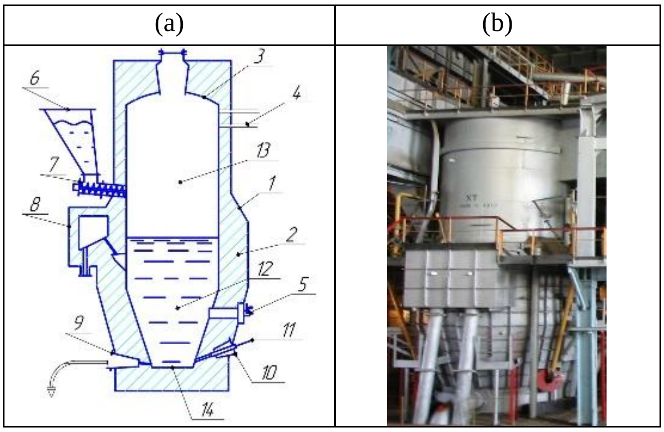

Figure 5. Chlorinator: (a) – schematic view; (b) – general view: 1 – shell; 2 – fireclay brick lining; 3 – dome; 4 – main gas duct; 5 – graphite electrode; 6 – intermediate feed bunker; 7 – screw feeder; 8 – upper slag tapping port; 9 – lower slag tapping port; 10 – tuyere assembly; 11 – chlorine pipeline; 12 – molten zone; 13 – vapor-gas zone; 14 – hearth

The condensation units were maintained at controlled temperatures to ensure selective separation:

– 400-600°C – dust chamber for solid sublimates ($NbOCl_3$, $VOCl_3$);

– 300-320°C – salt bath melt condenser for semi-volatile species;

– 100-160°C – scrubber system for soluble chlorides;

– <20°C – spray condenser for high-purity $TiCl_4$ recovery.

Sampling was performed at all process stages daily. Composite samples were prepared every 10 days for monthly analysis. The niobium content in raw slag was measured via atomic emission spectroscopy (AES) using a DFS-458 spectrometer, while chlorinator discharge slag, dust, salt bath residues, and scrubber slurries were analyzed by photometric methods involving niobium PAR complex formation in a tartaric-HCl medium, followed by absorbance quantification with a KFK-3 photocolorimeter [10].

Quantitative niobium distribution was assessed by recalculating its mass across process outputs per ton of feedstock, using monthly datasets collected from 2019 to 2024 across varying slag compositions and chlorination campaigns.

3. Results and discussion

3.1 Niobium occurrence in ilmenite and behavior in slag

Mineralogically, ilmenite ($FeTiO_3$) belongs to the subclass of complex oxides within the trigonal crystal system. It often serves as a primary source of titanium dioxide (TiO_2) for metallurgical and pigment applications. In addition to titanium and iron, natural ilmenite frequently contains trace elements such as vanadium, chromium, and particularly niobium, which can be present in varying amounts depending on the geological origin of the deposit.

The Nb_2O_5 content in natural ilmenite has been reported to vary significantly: from 0.26-1.44 wt.% in agpaitic pegmatites and from 0.93-1.55 wt.% in miaskitic pegmatites, both types of alkaline rocks associated with complex rare-element mineralization. These values suggest that certain ilmenite deposits may serve as secondary sources of niobium. Spectrochemical analysis of ilmenite from the Volnogorsk deposit (Ukraine) shows an average Nb_2O_5 content of approximately 0.034%, while in Satpayev ilmenite (Kazakhstan), the content is around 0.02%.

During carbothermic smelting of ilmenite concentrate at elevated temperatures (~1500-1700°C), most of the iron is reduced to metal or enters the slag as FeO, while titanium remains as TiO_2-rich slag. Niobium, being less reducible than titanium or iron, remains entirely in the oxide form and accumulates within the titanium slag phase. The Gibbs free energy (ΔG) for the reduction of Nb_2O_5 by carbon at 1500°C is +1564.6 kJ, indicating that the direct reduction of niobium pentoxide by carbon is thermodynamically unfavorable under standard metallurgical conditions. This explains its persistence in the slag phase post-smelting.

3.2 Thermodynamic considerations and chlorination environment

Chlorination experiments were performed on the titanium slag in a molten salt medium within a temperature range of 700-820°C. The salt composition typically included alkali and transition metal chlorides, approximated as (% wt.): NaCl – 19-24.5; KCl – 16.7-20; $MgCl_2$ – 1-11.7; $FeCl_2$ – 8-26; $FeCl_3$ – 0.8-2; $AlCl_3$ – 1.5-4. These chlorides served multiple roles: as a heat transfer medium, a diluent, and a reactive agent facilitating chlorination of refractory oxides.

According to literature, niobium in chloride melts can exist in various oxidation states and coordination environments. It is widely accepted that high-valent niobium, particularly Nb^{5+}, forms stable octahedral anionic complexes such as $[NbCl_6]^-$. In reducing environments or with high chloride activity, tetravalent complexes like $[NbCl_6]^{2-}$ and even lower-valent or cluster species can be stabilized. These species demonstrate different volatilities and reactivities, which is significant for understanding their behavior in the chlorination and condensation circuits.

Analytical monitoring of the chlorinator melts after prolonged operation revealed an average Nb_2O_5 concentration of ~0.05%. This suggests gradual but consistent enrichment of the melt in niobium-containing species during chlorination.

3.3 Reactions of niobium during chlorination

Niobium present in the titanium slag undergoes several thermodynamically favorable transformations in the presence of chlorine gas and carbon as a reducing agent. The primary reactions include:

$$2Nb_2O_5 + 6Cl_2 + 3C \rightarrow 4NbOCl_3 + 3CO_2, \quad \Delta G = -594.8 \text{ to } -563.6 \text{ kJ}. \tag{1}$$

$$2Nb_2O_5 + 10Cl_2 + 5C \rightarrow 4NbCl_5 + 5CO_2, \quad \Delta G = -987.5 \text{ to } -974.9 \text{ kJ}. \tag{2}$$

$$2Nb_2O_5 + 6Cl_2 + 5C \rightarrow 4NbCl_3 + 5CO_2, \quad \Delta G = -527.2 \text{ to } -534.2 \text{ kJ}. \tag{3}$$

These reactions illustrate the stepwise reduction and chlorination of niobium pentoxide to various chlorinated forms, depending on the redox conditions and chlorine partial pressure. Empirical studies [16] have shown that the chlorination of Nb_2O_5 typically results in a mixture of $NbOCl_3$ and $NbCl_5$, formed via the following overall reaction:

$$Nb_2O_5 + 4Cl_2 + 2C \rightarrow NbOCl_3 + NbCl_5 + 2CO_2, \quad \Delta G = -395.8 \text{ to } -384.6 \text{ kJ}. \tag{4}$$

Chlorinated niobium species enter the vapor phase and migrate downstream in the gas flow. $NbOCl_3$ sublimes at ~400°C, and $NbCl_5$ has a boiling point of 248.3°C, both well below the operating temperature of the dust chamber (500-600°C), ensuring they remain in the gas phase through this section.

3.4 Condensation and niobium concentration in slurry

Upon entering the salt bath condensation chamber (SBC), where the temperature is maintained at 300-350°C, $NbOCl_3$ condenses into the salt melt due to its lower volatility [17]. The concentration of niobium in the SBC melt, again expressed as Nb_2O_5, was found to be ~0.05%. $AlCl_3$ in the SBC reached up to 40 wt.%, influencing redox equilibria. Under these conditions, a secondary reaction proceeds:

$$NbOCl_3 + AlCl_3 \rightarrow NbCl_5 + AlOCl, \quad \Delta G = -3.5 \text{ to } -3.2 \text{ kJ}. \tag{1}$$

This transformation increases the concentration of volatile $NbCl_5$, which is more prone to carrying over into downstream zones. Observations revealed that dilution of the SBC melt (due to excess slag or scrubber return) led to reduced $AlCl_3$ concentrations and correspondingly lower niobium concentrations in the final slurry. Thus, maintaining high $AlCl_3$ levels appears beneficial for enhanced niobium transfer.

In the final condensation zone the irrigated scrubber, the gas stream is cooled below 125°C. Since $NbCl_5$ condenses at 248.3°C, complete condensation occurs here. Niobium precipitates in the $TiCl_4$ pulp as fine, yellowish, acicular crystals. The total solid content of the pulp may reach up to 100 g/L, with the niobium-rich fraction exceeding 20 wt.% as Nb_2O_5.

3.5 Industrial data and discussion

Between 2019 and 2024, a series of trials were conducted at titanium processing facilities using various combinations of titanium slag from JSC «UK TMP» (Kazakhstan) and TiZir Titanium & Iron AS (Norway). These experiments involved blending the slags in different ratios (100/0, 60/40, 50/50, 30/70) to observe changes in niobium behavior. The analysis showed that average Nb_2O_5 content ranged from 0.036-0.050% in UK TMP slag and 0.057-0.067% in TiZir slag. Table 2 summarizes the distribution of niobium across process streams.

Table 2. Distribution of niobium among process products

No.	Ti Slag Ratio (UK TMP /TiZir)	Average Nb_2O_5 Content, %	Distribution of Nb, %			
			Dump slag	Sublimates from the dust chamber	Melt from the salt-bath condensation chamber	Irrigated scrubber slurry
1	100/0	0.045	51.0	3.4	2.1	43.5
2	60/40	0.049	46.8	4.5	2.9	45.8
3	50/50	0.052	45.1	4.2	2.1	48.6
4	30/70	0.058	42.7	2.0	1.3	54.0

The data suggest that higher proportions of TiZir slag, which contains more Nb, promote niobium enrichment in volatile and condensable fractions (dust, melt, slurry), while decreasing its retention in the dump slag. This trend is consistent with the formation of more volatile niobium chlorides under higher Nb feed conditions. Therefore, from a process engineering standpoint, the increase in TiZir slag fraction enhances niobium recovery in downstream process products, especially in the slurry where its selective extraction may be most feasible.

4. Conclusions

Thus, during the chlorination of titanium-containing feedstock in the presence of a reducing agent such as carbon, niobium initially retained in oxide form within the titanium slag undergoes chemical transformation into volatile chlorinated species. Specifically, niobium transitions into oxychloride forms such as $NbOCl_3$ and, under favorable conditions particularly in the presence of aluminum trichloride, converts to niobium pentachloride ($NbCl_5$). These processes are facilitated by the molten salt medium used during chlorination, which provides a chemically active and heat-stable environment conducive to complex reaction pathways.

Thermodynamic analysis based on calculated Gibbs free energy (ΔG) values confirms the feasibility and spontaneity of these transformations within the temperature range of 700-820 °C. The experimental findings align with theoretical predictions and with published literature data, reinforcing the understanding of niobium's behavior under industrial chlorination conditions.

Experimental methods, including chemical analysis of solid and liquid process streams, were employed to determine the average niobium content in both the raw feedstock and the intermediate products formed throughout the titanium tetrachloride production cycle. The results demonstrate the complex migration behavior of niobium, indicating that it does not remain inert within the slag but instead redistributes across several phases depending on reaction conditions and equipment configuration.

Industrial-scale trials involving the processing of titanium slags from two different sources JSC «UK TMP» (Kazakhstan) and TiZir Titanium & Iron AS (Norway) in various mass ratios (100/0 to 30/70) have shown clear trends in niobium distribution. Most of the niobium was found to accumulate in two main fractions: the dump slag from the chlorinator and the solid phase of the scrubber slurry, where temperatures are conducive to condensation and precipitation. Notably, as the initial content of niobium in the feed increases particularly with the use of higher TiZir slag proportions, the concentration of niobium in downstream products (dust chamber sublimates, salt bath melt, and scrubber slurry) also increases, while its content in the dump slag decreases. This redistribution pattern can be attributed to the formation of more volatile and thermodynamically stable niobium chlorides under higher feed concentrations.

These findings suggest that the most promising direction for the development and implementation of niobium recovery technology within titanium tetrachloride production lies in the targeted extraction from the dump slag and scrubber slurry. These process streams consistently demonstrate the highest concentrations of niobium and offer opportunities for selective recovery using hydrometallurgical or combined techniques. The data obtained from both laboratory and industrial experiments may therefore serve as a foundation for future technological solutions aimed at enhancing the overall efficiency of rare metal utilization in the titanium industry.

Author contributions

Conceptualization: TKS, TAC; Data curation: YEM, TKS; Formal analysis: YEM, TBY; Funding acquisition: TKS, TAC; Investigation: YEM, TBY; Methodology: TKS, TAC; Project administration: TKS, TAC; Resources: TAC, YEM; Software: YEM, TBY; Supervision: TKS, TAC; Validation: TKS, TAC; Visualization: YEM, TBY; Writing – original draft: TKS, TBY; Writing – review & editing: TKS, TAC. All authors have read and agreed to the published version of the manuscript.

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Conflicts of interests

The authors declare no conflict of interest.

Data availability statement

The original contributions presented in this study are included in the article. Further inquiries can be directed to the corresponding author.

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Хлорлау өңдеу процесінде ниобийдің әртүрлі титанды құрамды шикізаттарда таралуы

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Аңдатпа. Бұл мақалада «ӨТМК» АҚ (Қазақстан) компаниясының титан шлактары, норвегиялық TiZir Titanium & Iron AS компаниясының титан шлактары және олардың әртүрлі қатынастағы қоспалары сияқты әртүрлі титанды құрамды шикізатты хлорлау арқылы өңдеу барысында ниобийдің таралуын зерттеу нәтижелері ұсынылған. Титан шлак үлгілері ұсақталып, сілтілі металл хлоридтерінен ($MgCl_2$, KCl, NaCl) тұратын балқытылған тұз ортасында, қалпына келтіруші ретінде ұнтақталған антрацитпен бірге, концентрленген хлор газы арқылы хлорланды. Процесс 700-820°C температурада жүргізілді. Зерттеу барысында титанды шлактарды 60/40, 50/50 және 30/70 (ӨТМК/TiZir) қатынастарда, сондай-ақ 100% ӨТМК шлагында хлорлау кезінде ванадий мен ниобийдің таралу заңдылықтары анықталды. Зерттеу нәтижелері бойынша ниобийдің негізгі бөлігі титан хлораторынан шыққан шлакте және оросительді скруббер пульпасында жиналатыны анықталды. Сондай-ақ бастапқы шикізаттағы ниобий мөлшері артқан сайын оның шаң камерасындағы сублиматта, тұзды ваннаның шаңтұндыру камерасындағы балқымасында және скруббер пульпасындағы концентрациясы артып, ал хлоратор шлагындағы үлесі төмендейтіні байқалды.

Негізгі сөздер: *титан шлактары, ванадий, ниобий, таралу, титан, хлоратор шлактары, хлорлы сублиматтар, хлорлау, шлактарды өңдеу, ниобийді алу.*

Распределение ниобия при хлорной переработке различного титансодержащего сырья

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Аннотация. В данной статье представлены результаты исследования распределения ниобия при хлорной переработке различных титансодержащих сырьевых материалов, включая титановые шлаки АО «УК ТМК», титановые шлаки норвежской компании TiZir Titanium & Iron AS, а также их смеси в различных соотношениях. Образцы титанового шлака были измельчены и подвергнуты хлорированию с использованием концентрированного хлорного газа в расплаве солей щелочных металлов ($MgCl_2$, KCl, NaCl), при этом в качестве восстановителя использовался тонкоизмельчённый антрацит. Процесс проводился при температуре 700-820°C. Основное внимание в исследовании было уделено поведению ванадия и ниобия при хлорировании смешанных шлаков в соотношениях 60/40, 50/50 и 30/70 (АО «УК ТМК»/TiZir), а также в 100 % шлаке АО «УК ТМК». Результаты показали, что основное количество ниобия накапливается в отвальном шлаке титаново-хлорирующей установки и в пульпе оросительного скруббера. Также установлено, что с увеличением исходного содержания ниобия в сырье возрастает его концентрация в возгонах пылевой камеры, в расплаве солевой пылеосадительной камеры и в пульпе скруббера, тогда как его доля в отвальном шлаке снижается.

Ключевые слова: *титановые шлаки, ванадий, ниобий, распределение, титан, отвальный шлак, хлоридные возгоны, хлорирование, переработка шлаков, извлечение ниобия.*

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